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VEHICLE ATTITUDE CONTROL SYSTEM

by

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Mathematical Simulation of the Three-Channel Vehicle Attitude Control System

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Abstract: The necessity for and feasibility of developing mathematical simulation of the three-channel vehicle attitude control system as well as principles and methods to design the software of this simulation are described in this paper. Some examples of mathematical simulation of one-channel, two-channel and three-channel systems indicate that mathematical simulation of the three-channel system can reflect the full view and the performance index of the system completely and realistically, can exactly verify the correctness of the design theory, can provide more reliable reference curves for hardware-in-the-loop simulation of the system, and meanwhile provides important means and methods to increase the quality of the attitude system design.

Key Words: Launch vehicle, system simulation, mathematical simulation

Introduction

The design of an attitude control system is conducted in the frequency domain by using a solidity coefficient method with pitch, yaw, and roll as separate channels. The parameters of the system designed with one channel ensure the system stability, based on the system stability theory and by leaving an appropriate stability margin.

In the flight process of a launch vehicle, the respective variables of the pitch, yaw and roll channels are mutually dependent and mutually affecting. Since the end of the

seventies, the attitude control system mathematical simulation software has been designed on the basis of one channel. Similarly, in recent years, the two-channel and three-channel mathematical simulation software is also designed by simplifying the rocket body dynamics kinematic equation, such as by omitting the effect of the second order sway in the pitch and yaw channels on the roll channel, or ruling out the elastic and sway equations in the pitch (or yaw) channel. However, neither one-channel mathematical simulation nor simplified multi-channel mathematical simulation can completely and accurately reflect the flight law of the launch vehicle. While the three-channel overall equation mathematical simulation features the following advantages:

(1) It can arrive at an accurate theoretical design mathematical simulation result;

(2) It can provide system designers with a more complete and accurate simulation result to design a better attitude control system;

(3) It can produce multi-channel standard reference curves for use in half-object simulation; and

(4) It can help the half-object simulation find out problems, remove obstacles and increase its simulation efficiency.

This paper presents a tentative study and exploration of the design concept and methodology in the design of the launch vehicle attitude control system three-channel overall equation mathematical simulation software, from which much valuable experience has been gathered.

1. Vehicle Body Mathematical Model

The launch vehicle body mathematical model consists of two parts: vehicle body dynamics kinematic equation and vehicle body control equation.

1.1 Vehicle Body Dynamics Kinematic Equation

1.1.1 Pitch-channel Vehicle Body Dynamics Kinematic Equation

$$\Delta\theta + \sum_{P=1}^{4} c_{4p}\Delta\ddot{Y}_p = (c_2 - c_1)\Delta\theta + c_1\Delta\varphi + c_3\Delta\delta_\varphi + c''_3\Delta\ddot{\delta}_\varphi - \overline{F}_{YC}$$

$$\Delta\ddot{\varphi} + \sum_{P=1}^{4} b_{4p}\Delta\ddot{Y}_p = b_2(\Delta\theta - \Delta\varphi) - b_1\Delta\varphi - b_3\Delta\delta_\varphi - b''_3\Delta\ddot{\delta}_\varphi + \sum_{P-1}^{4} b_{5P}\Delta Y_p + \overline{M}zc \tag{1}$$

$$\ddot{q}_{iY} - \sum_{P-1}^{4} G_{ip}''\Delta\ddot{Y}_P = D_{2i}(\Delta\varphi - \Delta\theta) + D_{1i}\Delta\dot{\varphi} - \omega_1^2 q_{iy} - 2\zeta_i\omega_i\dot{q}_{iy}$$

$$+ \sum_{P=1}^{4} G_{ip}\Delta Yp + D_{3i}\Delta\delta_\varphi + D''_{3i}\Delta\ddot{\delta}_\varphi - \overline{Q}_{izc} \qquad (i = 1,2)$$

$$V\Delta\theta + X_{Pt}\Delta\ddot{\varphi} - \sum_{i=1}^{2} E''_{ip}\ddot{q}_{iy} + \Delta\ddot{Y}_p = -V\Delta\theta + (E_1 + V)\Delta\varphi$$

$$+ \sum_{i=1}^{2} E_{ip}q_{iy} + \Delta\Omega_p^2\Delta Y_p - 2\zeta_{p1}\Omega_p\Delta Y_p \qquad (P = 1,\ 2,\ 3,\ 4)$$

1.1.2 Yaw-channel Vehicle Body Dynamics Kinematic Equation

$$\sigma + \sum_{P=1}^{4} c_{4p}\Delta\ddot{Z}_p = (c_2 - c_1)\sigma + c_1\psi + c_3\ddot{\delta}_\psi + c''_3\delta_\psi - \overline{F}_{2c}$$

$$\ddot{\psi} + \sum_{P=1}^{4} b_{4p}\Delta\ddot{Z}_P = b_2(\delta - \psi) - b_1\psi - b_3\delta_\psi + b''_3\ddot{\delta}_\psi$$

$$+ \sum_{P=1}^{4} b_{5p}\Delta Zp + \overline{M}_{YC}$$

$$\ddot{q}_{iz} - \sum_{P=1}^{4} G''_{ip}\Delta\ddot{Z}p = D_{2i}(\psi - \sigma) + D_{1i}\psi - \omega_i^2 q_{iz} - 2\zeta i\omega i\dot{q}_{iz}$$

$$+ \sum_{P=1}^{4} G_{ip}\Delta Zp + D_{3i}\Delta\delta_\psi + D''_{3i}\Delta\delta_\psi - \overline{Q}_{iyc} \qquad (i = 1,\ 2)$$

$$V\dot{\sigma} + X_{pT}\ddot{\psi} - \sum_{i=1}^{2} E''_{ip}\ddot{q}_{iz} + \Delta\ddot{Z}_p = -V\Delta\sigma + (E_1 + V)\psi$$

$$+ \sum_{i=1}^{2} G_{ip}q_{iz} + \Delta\Omega_p^2\Delta Z_p - 2\zeta_{p1}\Omega_p\Delta\dot{Z}_p \qquad (P = 1,\ 2,\ 3,\ 4)$$

1.1.3 Roll-channel Vehicle Body Dynamics kinematic Equation

$$\ddot{\gamma} + d_3\delta_{\gamma} + d_3''\delta_{\gamma} = \ddot{M}_{BX} + k\sum_{P=1}^{4} m_{XP}\Delta\ddot{Y}_P + k\sum_{P=1}^{4} m_{XP}\Delta Z_P \tag{3}$$

$$\ddot{q}_{r1} + 2\omega_{r1}\zeta_{r1}\dot{q}_{r1} + \omega_{r1}^2 q_{r1} = d_{31}\delta_r + d_{31}\ddot{\delta}_{\gamma}$$

1.2 Vehicle Body Control Equation

$$\Delta\delta_{\varphi}^{*} = [a_a^{\varphi} W_{\mathrm{r}}(P)\Delta\varphi_{\mathrm{r}} + a_1^{\varphi} W_{g\mathrm{r}}(P)\Delta\dot{\varphi}_{g\mathrm{r}}]W_g^{\varphi}(P)$$

$$\Delta\delta_{\psi}^{*} = [a_a^{\varphi} W\Gamma(P)\psi_{\mathrm{r}} + a_1^{\psi} W_{g\mathrm{r}}(P)\dot{\psi}_{g\mathrm{r}}]W_g^{\varphi}(P)$$

$$\Delta\delta_{r}^{*} = [a_a^{r} W\Gamma(P)r_{\mathrm{r}} + a_1^{r} W_{\sigma r}(P)\dot{r}_{\sigma r}]W_g^{r}(P)$$

where $$\Delta\varphi_{\mathrm{r}} = \Delta\varphi - \sum_{i=1}^{2} W_i'(X_{\mathrm{r}})q_{iy}$$

$$\Delta\dot{\varphi}_{gr} = \Delta\dot{\varphi} - \sum_{i=1}^{2} W_i'(X_{gr})\dot{q}_{iy}$$

$$\psi_{\mathrm{r}} = \psi - \sum_{i=1}^{2} W_i'(X_{\mathrm{r}})q_{iz}$$

$$\dot{\psi}_{gr} = \dot{\psi} - \sum_{i=1}^{2} W_i'(X_{gr})\dot{q}_{iz}$$

$$r_{\mathrm{r}} = r + W_{H1}(X_{\mathrm{r}})q_{r1}$$

$$r_{gr} = \dot{r} + W_{H1}(X_{gr})\dot{q}_{r1}$$

where $W_r(P)$ is platform transfer function, which is a second order oscillatory integration link; $W_{gr}(P)$ is rate gyro-filter synthetic transfer function, which is composed of two second-order oscillatory integration links; $W_g^{\varphi}(P)$, $W_g^{\psi}(P)$, $W_g^{\gamma}(P)$ constitute a continuous system correction network whose numerator and denominator are both made of several first-order inertial links and second-order oscillatory integration links. $W_g^{\varphi}(P)$, $W_g^{\psi}(P)$, $W_g^{r}(P)$ can be converted to corresponding numerical control differential equations through bilinear transformation in the case when numerical control system simulation is needed.

1.2.1 One channel Helm Angle Computation Formula

$$\Delta\delta_{\psi} = \Delta\delta_{\psi}^{*} W_{Cn}(P)$$

$$\Delta\delta_{r} = \Delta\delta_{r}^{*} W_{Cn}(P) \tag{5}$$

where the numerator of $W_{C\pi}(P)$ is 1, while its denominator is composed of several first-order inertial links and second-order oscillation links.

1.2.2 Two-channel Rudder Angle Computing Formula

1.2.2.1 Pitch and Roll Channel Rudder Angle Computing Formula

$$
\begin{aligned}
\delta_{II} &= (-\Delta\delta_{\varphi}^{*} + \Delta\delta_{r}^{*})W_{C\pi}(P) \\
\delta_{IV} &= (\Delta\delta_{\varphi}^{*} + \Delta\delta_{r}^{*})W_{C\pi}(P) \\
\Delta\delta_{\varphi} &= \frac{-\delta_{II} + \delta_{IV}}{2} \\
\delta_{r} &= \frac{\delta_{II} + \delta_{IV}}{2}
\end{aligned}
\qquad (6)
$$

1.2.2.2 Yaw and Roll Channel Rudder Angle Computing Formula

$$
\begin{aligned}
\delta_{I} &= (-\delta_{\psi}^{*} + \delta_{r}^{*})W_{C\pi}(P) \\
\delta_{III} &= (\delta_{\psi}^{*} + \delta_{r}^{*})W_{C\pi}(P) \\
\delta_{\psi} &= \frac{-\delta_{I} + \delta_{III}}{2} \\
\delta_{r} &= \frac{\delta_{I} + \delta_{III}}{2}
\end{aligned}
\qquad (7)
$$

1.2.2.3 Three-Channel Rudder Angle Computing Formula

$$
\begin{aligned}
\delta_{I} &= (-\delta_{\psi}^{*} + \delta_{r}^{*})W_{C\pi}(P) \\
\delta_{III} &= (\delta_{\psi}^{*} + \delta_{r}^{*})W_{C\pi}(P) \\
\delta_{II} &= (-\Delta\delta_{\varphi}^{*} + \Delta\delta_{r}^{*})W_{C\pi}(P) \\
\delta_{IV} &= (\Delta\delta_{\varphi}^{*} + \Delta\delta_{r}^{*})W_{C\pi}(P)
\end{aligned}
$$

$$\Delta\delta_{\varphi} = \frac{-\delta_{II} + \delta_{IV}}{2}$$

$$\Delta\delta_{\psi} = \frac{-\delta_{I} + \delta_{III}}{2} \qquad (8)$$

$$\Delta\delta_{r} = \frac{\delta_{I} + \delta_{II} + \delta_{III} + \delta_{IV}}{4}$$

2. Characteristics of Vehicle Body Mathematical Model

To design a launch vehicle attitude control system mathematical simulation software highlighting an explicit structure, complete functions and convenient use, it is far from enough just to carry out an analysis of the requirements from the mathematical simulation instructions and select an appropriate algorithm. It requires an in-depth study of the characteristics of the system itself to design a high-quality mathematical simulation software. In this case, the launch vehicle attitude control system three-channel mathematical simulation model has many unique characteristics, apart from those of the one-channel mathematical model.

2.1 Characteristics of the Vehicle Body Dynamics Kinematic Equation

a. The vehicle body dynamics kinematic equation of the launch vehicle attitude control system consists of pitch, yaw and roll channels, and its kinematic law is described by a group of 34 first-order differential equations.

b. It is known from Eqs. (1) and (2) that the pitch channel and yaw channel vehicle body dynamics kinematic equations have the same structure and adopt the same variable coefficient value.

c. The differential equation group used to describe the launch vehicle attitude control system kinematic law is virtually an implicit second-order differential equation group, where the pitch and yaw channels are not cross-linked but they are cross-

linked with the roll channel simultaneously.

d. The elastic and sway equations of the pitch and yaw channels respectively have the same form.

2.2 Characteristics of Vehicle Body Control Equation

a. The rudder angle computation equations of the pitch, yaw and roll channels of the vehicle body attitude control system take the same form.

b. The pitch and yaw channels of the system use the same correction network, while the roll channel adopts a different one.

c. The synthetic rudder edge angle and its acceleration of the pitch, yaw and roll channels are derived through synthesis of the edge angle and its acceleration of the final control mechanism.

2.3 Characteristics of Vehicle Body Parameters

a. A huge diversity of data types.

The original data of the launch vehicle attitude control system can be divided into two parts in terms of its location, namely: 1) vehicle body equation coefficients and 2) various measurement and design parameters of the control equation. Between them the data of the vehicle body kinematic equation are more complex with as many as 14 variable coefficients.

b. Extremely nonuniform distribution of variable coefficients.

It is known from Section 1 that most of the variable coefficients of the launch vehicle are distributed in the vehicle body equation and only a few variable coefficients are found in the control equation.

c. Vast information content of data.

The three channels of the launch vehicle attitude control system have not only a large number of original variable coefficients, but also a great many simulation result curves, with each coefficient as well as each curve composed of numerous data.

3. Design of Attitude Control System Three-Channel Mathematical Simulation Software

3.1 Design Principle of Attitude Control System Three-channel Mathematical Simulation Software

a. The software must have an ideal and rational structure.

b. The software must have complete functions.

The software must have the functions of conducting mathematical simulation for continuous systems and digital systems, for constant coefficient and variable coefficient, and for one channel, two channels and three channels.

c. The software must be read, used, modified and maintained conveniently.

d. The software operating time must be reduced as much as possible under the condition that the simulation calculations meet the required precision.

3.2 Skills and Characteristics in Software Design

a. Designed with the modularization structure method, the launch vehicle attitude control system three-channel mathematical simulation software highlights features such as an explicit and rational structure as well as a high degree of modularization.

It is known from Section 2 that the launch vehicle attitude

control system generally consists of four major parts: the vehicle body equation, measurement equation, correction network and executive mechanism. Among them, the correction network involves a continuous network and a digital network, while the executive mechanism takes three modes--one channel, two channels and three channels. All the seven parts which are capable of independently accomplishing their own functions are programmed into standard modules in the above-described software. The standard modules with independent functions not only favor the software examination, debugging and modification, but also make the main control program concise and explicit. Table 1 shows the standard modules of the launch vehicle attitude control system mathematical simulation software.

Table 1 Standard Modules of Launch Vehicle Attitude Control System Mathematical Simulation Software

Name of Module	Function
DKWJ	Open the implementor name of the data file
CZ3A1	Output the editing original data
CZ3B1	Right function computation
CZ3C1	Data pre-processing
ZS3A1	Input initial conditions
ZS3A2	Initialization of working units
PSLD	Platform, rate gyro filter computation
LXJWJ	Continuous correction network computation
SZJWJ	Digital correction network computation
BθDAθ1	Fina- control mechanism one-channel control
BθDAθ2	Final-control mechanism two-channel control
BθDAθ3	Final-control mechanism three-channel control
PRIW1	Intermediate-result output module
PRIW4	Simulation-result output module

b. The structure of software main control program is rational.

The numerical control plan of the launch vehicle attitude control system is made of a continuous part and a discontinuous part. The former includes the vehicle body dynamics kinematic equation, measurement equation and executive mechanism, while the latter--numerical control differential equation. Generally, the computing step length of the numerical control differential equation is 20ms, but since the launch vehicle attitude control system is a typical rigid system, its integration step length should avoid being over-large, and 4-5ms is the usual choice to ensure computation stability. In other words, the continuous part should be computed 3-4 times for one-time computation of the differential equation. The same computing step length should be taken for the continuous plan. To make the software meet the requirements from both the continuous simulation and numerical control simulation, a combined algorithm is adopted, and the execution is designed in the order of differential equation, executive mechanism, vehicle body equation and measurement equation.

c. Link up individual modules by utilizing a common data block.

In the launch vehicle attitude control system three-channel mathematical simulation software, the source program contains 2200 FORTRAN statement lines, and there are 15 modules executing different functions apart from the main program. The modules alternatively use as many as 48 data sets and in such case, the dummy and real combination method is obviously over-complicated and likely to make mistakes. However, the three-channel mathematical simulation software, by setting a common data block,

can establish a common data block table putting data of different modules in an organic connection. This can facilitate software examination and debugging, provide convenience for software modification and maintenance and ensure the quality and reliability of the software.

d. Reach the goal of reducing computing load through decreasing the order number in solving the linear algebraic equation group.

It is known from Eqs. (1) and (2) that the vehicle body dynamics kinematic equations of the pitch and yaw channels are an implicit second-order differential equation group. To make computations synchronized and increase computation accuracy, the derivative values should be solved before being integrated. In solving the equation groups of (1) and (2), the derivative values can be obtained only through solving an eighth-order linear algebraic equation group. It is known from linear algebra that it takes $n/3(n^2+3n-1)$ multiply-divide operations to solve an n_{th}-order linear algebraic equation group. As the launch vehicle attitude control system has extremely high rigidity, an extremely small integration step length is needed for numerical integration so as to ensure stable computations. Suppose a rocket motion time is 120s and RK integration formula is adopted, then one step of integration would take four rotations of the right-hand function, which undoubtedly brings a tremendous computation load. It is found by investigating Eqs. (1) and (2) that the rigid body equation and elastic equation contain only the second-order sway quantity, and one equation does not contain the other equation's higher order derivative quantities; the sway equation contains the higher-order derivative term of the rigid body equation and elastic equation. 2.1 states that different sway equations have the same form, so it is easy to remove the higher-order derivative term of the rigid body and elastic equations through

artificial elimination to make the equations reduce to a fourth-order linear algebraic equation group. Table 2 displays the numbers of multiply-divide operations in calculating the right-hand function derivative value of Eqs. (1) or (2) indicating that the right function calculation load can be decreased by 53.71% through deformation processing of the equations.

Table 2. Numbers of Multiply-Divide Operations in Calculating Right-Hand Functions

2 次数 3 项目 / 1 类型	6 右端项	7 消元		10 回代	11 解方程组	12 累计
		8 系数行列式	9 右端			
公式未变形 4	90	–	–	–	232	322
公式变形 5	90	52	13	16	36	207

Key: (1) Type; (2) Times; (3) Term; (4) Undeformed equation; (5) Deformed equation; (6) Right-hand final term; (7) Elimination; (8) Coefficient determinant; (9) Right-hand end; (10) Reinsert; (11) Equation group to be solved; (12) Total

e. Reduce computation load by using group solution of linear algebraic equation group.

Section 2.1 states that the pitch and yaw channels in the launch vehicle attitude control system vehicle body dynamics kinematic equation share the same structure and take the same variable coefficient and also, the vehicle body equations of the two channels do not cross-link directly, while their mutual effect is realized through synthetization of rudder angles. Since the pitch and yaw channels have the same coefficient determinant, the higher-order derivative values of the two channels can be calculated by group solution of the linear algebraic equation group. According to the linear algebraic computation method, it takes $\frac{n(n^2-1)}{3} + Pn^2$. multiple-divide operations to solve the P linear equation group with the same coefficient determinant. Table 3 lists the number of multiply-

divide operations needed in calculating the right-hand function derivative values of the pitch and yaw channels indicating that group solution can save computation load by 17.39%.

Table 3. Numbers of Multiply-divide Operations Needed in Calculating Pitch and Yaw Right Functions

2 次数 1 项目 类型 3	6 右端项	7 消元		10 回代	11 解方程组	12 累计
		8 系数行列式	9 右端			
4 不成组解方程	180	104	26	32	72	414
5 成组解方程	180	52	26	32	52	342

Key: (1) Term; (2) Times; (3) Type; (4) Non-group equation solution; (5) Group equation solution; (6) Right-hand final term; (7) Elimination; (8) Coefficient determinant; (9) Right-hand end; (10) Reinsert; (11) Equations to be solved; (12) Total

f. Rational data classification and combination.

With numerous input and output data, rational classification and combination of data would be helpful for software compilation and examination, as well as for data retrieval, modification and usage. Otherwise, the correctness of data can hardly be ensured, and the designed software will surely be in disorder and difficult to read.

In the launch vehicle attitude control three-channel mathematical simulation software, the original data are classified based on the location of the data and the number of time nodes of the variable coefficients. Generally, the variable coefficients located in the vehicle body equation are put in one place, and the parameters in the control equation in another place and similarly, the rigid body and sway data with more corresponding time nodes are put in one place, and the elastic

data with less time nodes in another place.

The simulation result data are classified in accordance with the channel type and the variable character.

g. With complete functions, the software can accomplish mathematical simulation missions in many different states.

By setting a variety of information control variables in this software, users can perform mathematical simulation missions in response to their own requirements through variable combination. Table 4 lists control information variables.

Table 4 Control Information Variables

Serial number	Variable name	Content
1	IBDX	1 One channel 2 Two channels 3 Three channels
2	IFP	1 Two channels pitch+roll 2 Two channels yaw+roll
3	IABC	1 Rate 2 Upper limit 3 Lower limit
4	IABD	Under the condition of IABC≠1 1 Computation of upper and lower limit states 2 Computation of upper and lower extreme limit states
5	KLD	1 Numerical control system 2 Continuous system
6	KCB	1 Variable coefficient 2 Constant coefficient
7	KCB2	Under the condition of KCB=2 1 Initial conditions identical to those of the variable coefficient 2 Initial conditions are keyed in from terminal
8	IGS	1 Derivative value not to be solved 2 Derivative value to be solved
9	IKR	1 RK method 2 Implication Yula method 3 Improved Yula method

h. With an excellent man-machine interactive interface, this software is convenient to use. Users can arrive at a correct simulation result by just keying in necessary control information through the computer terminal screen to get the software operate.

4. Analysis of Simulation Result

With various interferences, the launch vehicle attitude control system three-channel overall equation mathematical simulation software completed 40 mathematical simulation missions in different states for continuous and numerical control systems, variable and constant coefficients, one, two and three channels. As a result, a large amount of useful simulation data were derived, which provided correct and satisfactory simulation results for the designers. A brief analysis of the simulation results is given as follows:

a. The one-channel mathematical simulation for the system, made in our project, confirmed the correctness of the system design. However, without considering the effect of inter-linking effect of different channels, the one-channel mathematical simulation cannot produce the engine synthetic oscillatory-angle-variation law curve and the maximum synthetic oscillation-angle-value that system designers are interested in. With this scenario, the system designers can only use the rudder edge angle derived from one channel, and make a rough estimation of the maximum engine oscillation angle with Eqs. (6) and (7).

b. The two-channel mathematical simulation considers the

channel inter-linking effect but only in part and thereby, the result is incomplete and not real, while the three-channel mathematical simulation takes the inter-linking effect among different channels into overall consideration and can offer a real and convincing simulation result. Table 5 shows the maximum engine oscillation angle values.

Table 5. Maximum Engine Oscillation Angle Values

Serial number One channel Two channels Three channels

1 序号	2 单通道	3 双通道	4 三通道
δIII	43.0346	44.11544	42.69880
δIV	48.8282	44.39694	42.98101

Table 5 indicates that the engine synthetic maximum oscillation angle derived from the three-channel mathematical simulation proves to be smaller than that given by one-channel and two-channel mathematical simulation. Eventually, the three-channel mathematical simulation favors optimizing the system design parameters and increasing the quality of the attitude control system.

5. Conclusions

a. With correct design concept, rational software structure and feasible technical approaches, the launch vehicle attitude control system three-channel mathematical simulation software served as the necessary advance research intended for the overall development of designing such software, and gathered some experience.

b. The three-channel simulation software overcame the disadvantages of the single-channel and simplified multi-channel mathematical simulation and therefore provided more correct and

reliable simulation results for the theoretical design.

c. This software provided more accurate and reliable standard simulation curves in use for half-object simulation. The half-object three-channel simulation requires a large amount of equipment and instrumentation, personnel, as well as a long time for preparation. In addition, its simulation result is associated with the quality of the equipment, instrumentation and objects involved. And usually, such simulation needs mathematical simulation curves as reference curves. The three-channel mathematical simulation can provide the half-object simulation with standard simulation curves.

b. Mathematical simulation can execute simulation of the launch vehicle attitude control system under various conditions with only a small staff without using any objects and equipment except for computers, which is impossible in half-object simulation. In some way, the mathematical simulation, if well done, can reduce the working load of the half-object simulation. In some special cases, such as a limited time, temporary incompleteness of object equipment, etc., the mathematical simulation is in a position to replace the half-object simulation.

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